

JCSDA Community Radiative Transfer Model (CRTM)

*Fuzhong Weng¹, Yong Han^{1,2}, Paul van Delst^{2,3}, Quanhua Liu^{2,4}, Tom Kleespies¹,
Banghua Yan^{2,4} and J. Le Marshall²*

1. NOAA/NESDIS/Office of Research and Applications, Camp Springs, MD

2. Joint Center for Satellite Data Assimilation, Camp Springs, MD

3. CIMSS, University of Wisconsin, Madison, Wisconsin

4. QSS Group, Inc.

Abstract – The US Joint Center for Satellite Data Assimilation (JCSDA) has developed its beta version of community radiative transfer model (CRTM). The CRTM is being implemented in the NCEP data assimilation system and is expected to produce significant impacts on utilization of current and future satellite instruments due to its flexible interface, advanced radiative transfer physical processes and efficiency and effectiveness of numerical computational schemes. The advanced physics in the CRTM includes Optimal Spectrum Sampling (OSS), land microwave emissivity, discrete ordinate method and successive order of interaction scheme for scattering and emitting atmospheres, to name a few.

Introduction

A computationally efficient and accurate radiative transfer model is needed to compute radiances and Jacobians for satellite data assimilation. In the absence of atmospheric scattering, the components used in the data assimilation systems such as atmospheric absorption coefficients and the gradient of radiance relative to a state variable can be efficiently computed from the accurately parameterized models (Eyre, 1989; Garand et al., 2001). Thus, the radiance measurements from satellite sounding instruments under clear atmospheres have been most successfully assimilated into global numerical weather prediction (NWP) models.

To fully utilize the information of satellite measurements under all weather conditions for NWP, forward modeling capability needs to be enhanced to include both scattering and polarization processes. Cloud affected satellite radiances generally have not been assimilated into operational forecasting models although the measurements contain considerable information pertinent to the atmospheric hydrological cycle. In the next decade, many advanced infrared and microwave sensors will be deployed in space and their sensitivity to various atmospheric and surface parameters is significant. The uses of cloudy radiances in NWP models will ultimately enhance the impacts that have been demonstrated presently through clear radiance assimilation and add to our knowledge of clouds, the surface and the hydrological cycle.

In this paper, we will review several new aspects critically important for the developments of the community radiative transfer model (CRTM). The beta version of the CRTM is being released to NWP centers for the direct radiance assimilation and also to other users.

Community Radiative Transfer Model

Satellite radiances are not components of atmospheric state vectors predicted by NWP models. For radiances to be assimilated by NWP models, a relationship between the model state vectors and the observed radiances is required. This is provided by forward radiative transfer models with the state vectors as input (Figure 1). In addition, the Jacobian vector (or the derivative of radiance relative to the state vector) is also needed for satellite radiance assimilation.

The several schemes are proposed to discretize differential and integral radiative transfer equation and provide the solution for the radiative transfer in the vertically-stratified plan parallel

atmosphere. This part in the CRTM is referred as a RT solution module. Several RT solution modules are being tested, including 1) a vector discrete ordinate model (VDISORT) originally developed by Weng (1992), and several improved versions (Schulz et al., 1999; Weng and Liu, 2003); 2) Successive Order of Interaction (SOI) (Greenwald et al., 2004); 3) delta-four stream vector radiative transfer (DS4) (Liou et al., 2004) and 4) fast multi-stream scattering-based Jacobian for microwave radiance assimilation (Voronovich et al., 2004). The RT solution module to be selected for the CRTM implementation will be largely dependent on several critical facts provided by each investigator (e.g. speed, accuracy, storage for coefficients, Jacobian, potential developments for future instruments).

Under clear atmospheric conditions, radiative transfer modeling uses atmospheric absorption coefficients as the key input. The absorption varies with the atmospheric conditions in a complicated way and is often computed through the line-by-line (LBL) models. Although LBL models are accurate, they take considerable time to calculate transmittances for just a few atmospheres. To provide accurate transmittances in a timely fashion, the JCSDA has generated and used fast approximation commonly known as OPTRAN for specific instrument channels. For atmospheric transmittance calculations, the gas absorption coefficients are predicted from the atmospheric parameters at fixed levels of the integrated absorber amount (Kleespies et al., 2004). This approach significantly reduces the coefficients which reside in computer memory and preserves the accuracy.

Recently, a fast and optimal spectral sampling (OSS) absorption model which is developed by AER Inc. (Moncet *et al.*, 2004) is being tested and integrated as part of CRTM. The OSS is a new approach to radiative transfer modeling which addresses the need for algorithm speed, accuracy, and flexibility. The OSS technique allows for a rapid calculation of radiance for any class of multispectral, hyperspectral, or ultraspectral sensors at any spectral resolution operating in any region from microwave to ultraviolet wavelengths by selecting and appropriately weighting the monochromatic radiances contributed from gaseous absorption and particle scattering over the sensor bandwidth. This allows for the calculation to be performed at a small number of spectral points while retaining the advantages of a monochromatic calculation such as exact treatment of multiple scattering and/or polarization. The OSS method is well suited for remote sensing applications which require extremely fast and accurate radiative transfer calculations: atmospheric compensation, spectral and spatial feature extraction, multi-sensor data fusion, sub-pixel spectral analysis, qualitative and quantitative spectral analysis, sensor design and data assimilation. The OSS was recently awarded a U.S. Patent (#6,584,405) and is currently used as part of the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) CrIS, CMIS, and OMPS-IR environmental parameter retrieval algorithms. With the OSS method, the channel radiance is calculated from

$$\bar{R} = \int_{\Delta\nu} \phi(\nu)R(\nu)d\nu \cong \sum_{i=1}^N w_i R(\nu_i); \quad \nu_i \in \Delta\nu$$

where ν_i represents the wavenumber node and w_i is the weight determined by fitting “exact” calculations (from line-by-line model) for globally representative set of atmospheres (training set). At the selected nodes, the look-up tables of absorption coefficients for relevant species are stored. Maximum brightness temperature errors from the current look up table calculations are less than 0.05K in infrared and are about 0.01K in microwave wavelengths.

Note that both radiance and Jacobian computations require accurate knowledge of surface emissivity and reflectivity. Without an emissivity model, the measurements from those channels of current and future advanced sounders that are sensitive to the lowest atmospheric layers may not be assimilated into NWP models. As a critical part of the radiative transfer model (see Fig. 1), the surface emissivity model should be developed to properly include the variability of both emissivity and reflectivity. For the CRTM developments, the theoretical and technology advances to quantify the emissivity spectrum for various sensors of the global environment are highly encouraged.

The CRTM is being built on the existing surface emissivity modeling. With the launch of the first AMSU in 1998, an ocean microwave emissivity model developed by NESDIS was successfully implemented into the NCEP global data assimilation system. In collaboration with NCEP, NESDIS also tested and compared two ocean emissivity models. It was found that the model developed by the Metoffice, United Kingdom (English and Takashima, 1998) produced better results in assimilating the AMSU data, especially at high latitudes.

JCSDA Community Radiative Transfer Model

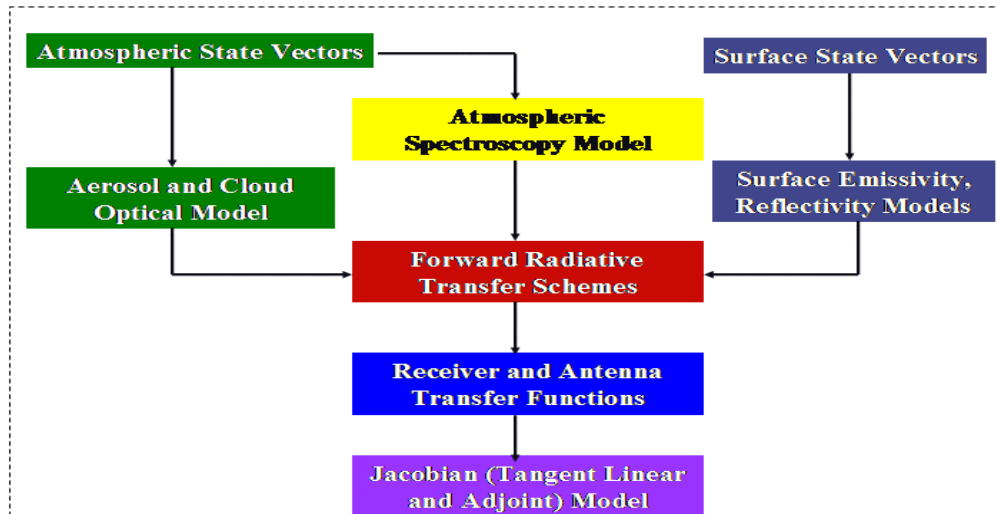


Figure 1. Components of the JCSDA community radiative transfer model (CRTM)

Over land, the NESDIS developed a microwave land emissivity model (Weng et al., 2001). This model capitalizes on scientific advances in various fields from atmospheric sciences to electrophysics and astrophysics. In particular, the volumetric scattering theory developed by the electrical engineering community is utilized to compute the optical parameters of snow, deserts and canopy leaves. In addition, the radiative transfer theory that is often applied in atmospheric science is enhanced to compute the bulk-emitted radiation from surface. The surface emission and scattering models also include the roughness effect that is approximated by the small perturbation theory. The radiation interaction between snow interfaces and volumetric scattering of particles is fully represented. In the case of vegetation, geometrical optics is used since the leaf size is typically larger than the wavelength. Critical issues remain in simulating the emissivity spectra over extreme surface conditions and at infrared wavelengths. Evidence of these model deficiencies comes from comparisons of the simulated global emissivity distribution with satellite retrievals from the AMSU and SSM/I (Weng et al., 2001). In cold climate regimes (e.g., Greenland), snow structure is very complex with stratification and metamorphosis.

From visible to infrared wavelengths, the emissivity over land is derived from a look-up table, according to surface type and wavelength. In the table, the emissivity spectra are specified as function of surface types including water, old snow, fresh snow, compacted soil, tilled soil, sand, rock, irrigated low vegetation, meadow grass, scrub, broadleaf forest, pine forest, tundra, grass soil, broadleaf pine forest, grass scrub, oil grass, urban concrete, pine brush, broadleaf brush, wet soil, scrub soil, broadleaf 70-pine 30, and new ice. Currently, the JCSDA is also developing infrared

emissivity estimates through use of high spectral resolution clear radiances and statistical or minimum emissivity techniques. These methods are being evaluated and are viewed as a prelude to using emissivity as part of a variational minimization in analysis.

For oceans, a model was developed to simulate the emissivity vector using a two-scale roughness approximation (Yueh, 1997). The emission from large-scale waves is normally polarimetric and is modeled by the geometrical optics (GO) (Stogryn, 1967). In the GO model, the large-scale waves are modeled by tilting surface facets, and the scattering coefficients are proportional to the number of surface facets with a sloping angle satisfying the specular reflection condition. The slope distribution of the large-scale roughness is computed from an ocean surface spectrum (Cox and Munk, 1954; Durden and Vesecky, 1985). However, the GO scattering theory underestimates the directional signals in the first three components of the microwave emissivity vector and predicts no signals in the fourth component (Gasiewski and Kunkee, 1994). Bragg scattering from the small-scale waves was found to be useful in explaining the dependence of the emissivity on ocean wind direction and the existence of the fourth component in the emissivity vector (Yueh, 1997). The cutoff wavenumber for separating between the large and small-scale waves depends on frequency and can be optimally derived (Liu et al., 1998). With a two-scale model, the emissivity and brightness temperature vectors can be simulated and are found to be consistent with those obtained from an airborne microwave radiometer (St. Germain and Poe, 1998). A similar model theory is also applicable for infrared wavelength (Wu and Smith, 2000) and integrated into CRTM.

Needed Community Contributions

The JCSDA CRTM design is still in its infancy stage. Many future developments are planned. For example, gas absorption models should consider more minor gases such as carbon monoxide because the forecast models are making more use of satellite measurements that are sensitive to them. Presently, transmittance models only include a number of "fixed" gases, and variable gases such as water vapor and ozone. Assimilating the satellite measurements into forecasting models and predicting their distributions require the transmittance models that include variations in minor gases. As the gas absorption models and other radiative transfer components become more accurate, the variations in retrieved temperature due to changes in minor gases become significant when they are ignored. For these reasons, future fast models will have to be modified to include the effects of these minor gases. In the short wavelength regions near 4 microns, aerosols begin to have some significant effect. Aerosols from volcanic eruption can affect the radiation at other spectral intervals as well and should be included in the forward model calculation.

Currently, cloudy and precipitating satellite radiances are not assimilated into operational forecasting models although the measurements contain crucial information on the atmospheric hydrological cycle. To utilize fully the information of satellite measurements under all weather conditions for NWP, one needs to extend the forward modeling capability to clouds and precipitation and their associated radiative processes of absorption, scattering, and polarization.

In surface modeling areas, the issues remain critical in simulating the emissivity spectra over specific surface conditions and at infrared wavelengths. The convincing evidences on the model deficiency are obtained through comparing simulated global distribution with satellite retrievals from the AMSU and SSM/I. In cold climate regimes (e.g. Greenland), snow structure is very complex with stratification and metamorphosis. The radiation interaction within the snow layers with volumetric scattering of particles needs to be understood.

Presently, our capability of simulating the sea ice emissivity is very limited, probably at best to the condition of newly formed first year sea ice. The needs for developing and testing the polarimetric emissivity model is urgent for assimilating the advanced instruments such as WindSat/Coriolis which was launched by the US Navy and is now used for the risk reduction study of CMIS aboard future National Polar-orbiting Operational Environmental Satellite System (NPOESS) satellites. Our

overall ability in simulating accurately ocean microwave emissivity is still limited within the frequencies lower than 100 GHz.

In summary, the JCSDA will work with the community in these areas:

1. Continue refining the rapid gas absorption model for current and many future sensors, including the absorption coefficients for hyperspectral instruments such as AIRS, IASI, CrIS and HES and the corresponding Jacobian codes when changes are required,
2. Update rapid atmospheric gaseous absorption coefficients as instrumental parameters, spectral knowledge, or requirements change. This includes the running of the LBL code as required, the integration of the LBL forward model calculation with the instrumental response functions and the generation of new fast model coefficients,
3. Develop and improve radiative transfer models to include scattering, polarization and polarimetry for assimilating the cloudy radiances,
4. Improve the performance of the microwave emissivity model over land and snow conditions, which will lead to more uses of sounding data over land and polar environments,
5. Develop fast land emissivity and reflectivity models for advanced infrared instruments,
6. Develop more comprehensive models to simulate the emissivity for new, second and multiyear sea ice,
7. Improve the performance of the current microwave emissivity model at higher frequencies (greater than 100 GHz),

Acknowledgments and Disclaimer - This study is supported under JCSDA science development and implementation fund, The views, opinions, and findings contained in this report are those of the authors and should not be construed as an official National Oceanic and Atmospheric Administration or U. S. Government position, policy, or decision.

REFERENCES

- Cox, C. S., and W. H. Munk, 1954: Measurement of the roughness of the sea surface from photograph's of the sun's glitter, *J. Opt. Soc. Amer.*, **44**, 838 - 850.
- Durden, S. P. and J. F. Vesecky, 1985: Physical radar cross-section model for a wind-driven sea with swell. *IEEE J. Oceanic Eng.*, **OE-10**, 445-451.
- Errico, R. M., 1997: What is an adjoint? *Bull. Amer. Meteor. Soc.*, **78**, 2577 – 2591.
- Eyre, J. R., 1989: Inversion of cloudy satellite sounding radiances by non-linear optimal estimation. I: Theory and simulation for TOVS, *Q.J.R.M.S.*, **115**, 1001-1026.
- English, S. J., and Takashima, T. J. 1998: A fast generic millimeter-wave emissivity model, *Microw. Rem. Sens. of the Atm. Environ., Proceedings of SPIE*, **3503**, 288-300.
- Garand, L. and co-authors, 2001: Radiance and Jacobian intercomparison of radiative transfer models applied to HIRS and AMSU channels, *J. Geophys. Res.*, **106**, 24,017-24,031.
- Gasiewski, A. J. and D. B. Kunkee, 1994: Polarized microwave emission from water waves, *Radio Science*, **29**, 1449-1466.
- Greenwald, T., R. Bennartz, C. O'Dell, and A. Heidinger, 2004: Fast computation of microwave radiances for data assimilation using the successive order of scattering approximation, *J. Appl. Meteor.*, **44**, 960-966
- Goodberlet, M. A., and C. T. Swift, et al., 1989: Remote sensing of ocean surface winds with the SSM/I, *J. Geophys. Res.*, **94**, 14,547 - 14,555.

- Kleespies, T. J., van Delst, P., McMillin L. M., and J. Derber, 2004: Atmospheric Transmittance of an Absorbing Gas. 6. OPTRAN Status Report and Introduction to the NESDIS/NCEP Community Radiative Transfer Model. *Applied Optics*, **43**, 3103-3109.
- Liu, Q., C. Simmer, and E. Ruprecht, 1998: Monte Carlo simulations of the microwave emissivity of the sea surface, *J. Geophys. Res.*, **103**, 24,983-24,989.
- Liou, K-N, S. Ou, Takano and Q. Liu, 2005: A Polarized Delta-Four-Stream Approximation for Infrared and Microwave Radiative Transfer, to appear in *JAS*
- Moncet, J., G. Uymen, H E. Snell, 2004, Atmospheric radiance modeling using the Optimal Spectral Sampling (OSS) method, *SPIE Defense and Security Symposium*, 13 April 2004, Orlando, Florida: Conference 5425: Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery X, 5425-37.
- Stogryn, A. 1967: The apparent temperature of sea at microwave frequencies, *IEEE*, **AP-15**, 278 – 286.
- St. Germain, K. and G. Poe ,1998: Polarimetric emission model of the sea at microwave frequencies, Part II: Comparison with measurements. Washington, D.C., Naval Research Laboratory Report.
- Schulz, F. M., K. Stamnes and F. Weng, 1999: An improved and generalized discrete ordinate radiative transfer model for polarized (vector) radiative transfer computations, *Quant. Spectrosc. Radiat. Trans.*, **61**, 105-122.
- Voronovich A. G. and A. J. Gasiewski, 2004: A fast multistream scattering-based Jacobian for microwave radiance assimilation, *IEEE Trans. Geosci. & Remote Sens.*, **42**, 1749-1761.
- Weng, F., B. Yan, and N. C. Grody, 2001: A microwave land emissivity model, *J. Geophys. Res.*, **106**, 20,115-20,123.
- Weng, F., 1992: A multi-layer discrete-ordinate method for vector radiative transfer in a vertically-inhomogeneous, emitting and scattering atmosphere I: Theory. *J. Quant. Spectrosc. Radiat. Transfer*, **47**, 19 – 33.
- Weng, F. and Q. Liu, 2003: Satellite data assimilation in numerical weather prediction models, 1. Forward radiative transfer and Jacobian models under cloudy conditions, *J. Atmos. Sci.*, **60**, 2633 – 2646
- Wu, X., and W. L. Smith, 1997: Emissivity of rough sea surface for 8-13 um: modeling and verification. *Applied Optics*, **36**, 2609-2619.
- Yueh, S. H., R. Kwok, F. K. Li, S. V. Nghiem, and W. J. Wilson, 1994: Polarimetric passive remote sensing of ocean wind vectors, *Radio Sci.*, **29**, 799 – 814.
- Yueh, S. H., 1997: Modeling of wind direction signals in polarimetric sea surface brightness temperatures, *IEEE.Trans. Geosci. Remote Sensing*, **35**, 1400 – 1418.

Proceedings of the Fourteenth International TOVS Study Conference

Beijing, China
25-31 May 2005

